

Light Echoes of Ancient Transients with the Blanco CTIO 4m Telescope

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Abstract. For over a century, light echoes have been observed around variable stars and transients. The discovery of centuries-old light echoes from supernovae in the Large Magellanic Cloud has allowed the spectroscopic characterization of these events using modern instrumentation, even in the complete absence of any visual record of those events. Here we review the pivotal role the Blanco 4m telescope played in these discoveries.

1. Introduction

Light from an astronomical source may reach an observer directly or after being scattered by interstellar dust. In the latter case, the arrival of any variations from the source object will be delayed by the longer path length (relative to the direct path) - resulting in what is referred to as a light echo. (e.g., Couderc 1939; Chevalier 1986; Schaefer 1987; Xu et al. 1994; Sugerman 2003; Patat 2005). The first light echoes were discovered around a nova in 1901, Nova Persei, and shortly thereafter recognized as such (Ritchey 1901; Kapteyn 1902; Perrine 1903). Since then, light echoes have been observed around Cepheids (e.g., RS Puppis, Westerlund 1961), eruptive variables (e.g., V838 Monocerotis, Bond et al. 2003), young stellar objects (e.g., S CrA, Ortiz et al.

2010), and supernovae (SNe), both in the local group (e.g., SN 1987A, Crots 1988; Suntzeff et al. 1988) and beyond (e.g., 1991T, Schmidt et al. 1994, and many more since). A characteristic of all these light echo instances is that they were discovered serendipitously while the variable object or transient source was still bright.

The idea of learning more about historical SNe by finding and studying their scattered light echoes was first raised by Zwicky (1940), but the first dedicated surveys in the last century were not successful (van den Bergh 1965a,b, 1966; Boffi et al. 1999). However, at the turn of the 21st century the development of focal planes populated with large numbers of CCD detectors, in combination with advancements in telescope technology, allowed the astronomical community to undertake wide-field, time-domain surveys with unprecedented depth and area. This led to the first serendipitous discovery of light echoes of centuries-old SNe in the Large Magellanic Cloud (LMC) by Rest et al. (2005b) during the SuperMACHO survey (Rest et al. 2005a).

Such light echoes of ancient events give us a rare opportunity in astronomy: the direct observation of the cause (the explosion/eruption) and the effect (the remnant) of the same astronomical event. They also allow us to observe the explosion from different angles, and thence to map asymmetries in the explosion. In this paper, we discuss the crucial role of the Cerro Tololo Interamerican Observatory (CTIO) Blanco telescope in the discovery and follow-up of these light echoes.

2. Light Echoes in the LMC

The advent of CCDs and telescopes with large field-of-view allowed the astronomical community to monitor large areas of the sky down to (stellar) visual magnitudes of 23 and fainter. The CTIO Blanco 4m telescope hosted some of these first transient surveys. One, the microlensing survey SuperMACHO (Rest et al. 2005a), monitored the LMC over 5 years. They reduced the Mosaic II CCD images with an automated pipeline producing difference images and transient alerts, identifying tens of thousands of transients (Garg et al. 2007), variables (Garg et al. 2010), and the well-known light echoes of SN 1987A (Newman & Rest 2006; Sinnott et al. 2013). Besides these expected variable sources, the SuperMACHO Project also found extended features sharing characteristics with the SN 1987A light echoes, but with significantly slower apparent proper motions - a few arcsec yr^{-1} - and apparent motion vector directions inconsistent with SN 1987A light echoes (see Figure 1). In order to identify the sources of these light echoes, if they were indeed light echoes, Rest et al. (2005b) overplotted the apparent motion vectors on an image of the LMC (see Figure 2), and they found that the echo motions trace back to three of its youngest supernova remnants (SNRs): SNR 0519-69.0, SNR 0509-67.5, and SNR 0509-68.7 (N103B). These three remnants had also been identified as Type Ia events, based on the X-ray spectral abundances (Hughes et al. 1995). Using the apparent motion of their light echoes, the associated SNe were estimated to be between 400 and 800 years old (Rest et al. 2005b).

This was the first time that light echoes of ancient transients were discovered. It allowed us to spectroscopically these transients long after their light first reached Earth directly. Rest et al. (2008a) analyzed a light echo from SNR 0509-675, which showed broad emission and absorption lines consistent with a supernova spectrum. To first order, the observed light echo spectrum is the lightcurve-weighted integration of the transients' individual spectral epochs. Rest et al. (2008a) compared the light echo spectrum to a spectral library consisting of 26 SNe Ia and 6 SN Ib/c that were time-integrated,

corrected for the effect of being scattered by LMC dust, and reddened by transit through the LMC and the Galaxy. When the echo spectra were compared with the convolved SN spectra, they found that overluminous 91T-like SNe Ia with $\Delta m_{15} < 0.9$ (a light-curve shape parameter where smaller indicates a more luminous SN) matched the observed spectrum best (see Figure 3). An analysis of SNR 0509-675 X-ray spectra is in excellent agreement with this result (Badenes et al. 2008).

The fact that light echoes of ancient SNe were found in the LMC indicated that they also should be detectable within our own Milky Way Galaxy, and it inspired survey programs to identify light echoes of historic SNe in our own Galaxy. The challenge was to find the light echoes, since the search radius scales with the inverse distance. At this writing light echoes from two of the six historical supernovae, Tycho (Ia) and Cas A (IIb), have been located and spectroscopically classified (Rest et al. 2008b; Krause et al. 2008a,b). In addition to the spectral typing, light echoes also offer two more exciting scientific opportunities, 3D spectroscopy and spectroscopic time series of transients, which are described in the following sections using SN 1987A and η Carinae as examples.

2.1. 3D Spectroscopy of SN 1987A with Light Echoes

The appearance of SN 1987A in the Large Magellanic Cloud in 1987 was a watershed event for many aspects of supernova astrophysics. Soon after the outburst, it became apparent that there were significant amounts of both circumstellar dust (Crotts & Kunkel 1991; Crotts et al. 1995; Sugerman et al. 2005a,b) and interstellar dust (Crotts 1988; Suntzeff et al. 1988; Gouiffes et al. 1988; Couch et al. 1990; Xu et al. 1994, 1995) which occupied the region around the supernova within the every-growing light echo ellipsoid. At any given instant after the outburst, the intersections of the locations of interstellar dust with the light echo ellipsoid provides the observer with a set of distinct perspectives on the outburst which differ from our usual direct, line-of-sight perspective. By obtaining spectra of the outburst light scattered from the interstellar dust, it is possible to determine the degree of asymmetry of the outburst. Boumis et al. (1998) and Smith et al. (2003) successfully applied this same technique to characterize the luminous blue variable η Car from spectra taken of different locations in its surrounding reflection nebula. Rest et al. (2011a) used this technique with light echoes of Cas A — the first time that this technique has been applied to a SN.

Fig. 4 illustrates the collection of seven non-direct perspectives from which spectra were obtained and reported by Sinnott et al. (2013) to look for spectral line changes which might arise from asymmetry. In that work, the spectra of the light echo locations was corrected for the dust’s enhanced scattering at shorter wavelengths and then compared with a temporal library of spectrophotometry obtained at SAAO. Sinnott et al. (2013) found an excess in the $H\alpha$ P Cygni profile in the red-shifted emission and a blue-shifted “knee” at PA=16° for the light echo labelled LE016 - (see the red line Figure 5).

There is a clear pattern in the how the $H\alpha$ features change as a function of position angle. The nearly diametrically-opposite light echo at PA=186° has a complementary pattern of an excess in blueshifted emission and a redshifted “knee” - (see blue line in Figure 5) Despite the maximum perspective different being only $\sim 40^\circ$, the easily-detected spectral profile changes suggest very significant differences in the photosphere as seen from LE016 and LE186. Sinnott et al. (2013) found that a bipolar and asymmetric ^{56}Ni distribution with a symmetry axis aligned along positional angles 16°/186° would provide a scenario consistent with their light echo spectra and

the symmetry axis ($\sim \text{PA}=15^\circ$) of elongated ejecta measured by Wang et al. (2002) and Kjær et al. (2010). The sign of the radial velocities of ejecta measured by Kjær et al. (2010) are also consistent with the findings of Sinnott et al. (2013), tying the asymmetry in the photosphere at the time of the outburst to the emerging supernova remnant structure.

2.2. Spectroscopic Time Series of η Car’s Great Eruption with Light Echoes

In the idealized case where a scattering dust filament is infinitely thin, the intensity of a light echo is simply the projected light curve of the source transient. Thus spectroscopy of a single light echo can, in theory, provide spectra from individual epochs of the transient. However, the finite thickness of the scattering dust filaments and the effects of seeing cause the convolution of nearby epochs of the light echo profile into the observed spectrum (Rest et al. 2011b, 2012b). In the case of supernovae in our Galaxy and typical dust filaments, the temporal resolution is typically between 3 weeks to a couple of months. Only under the most favorable conditions (small PSF size with space-based observations and favorable dust thickness/inclination) is the convolution effect reduced to as short as 1 week (Rest et al. 2011b). However, for transients with longer time scales than SNe it is possible to resolve them even using ground-based spectroscopy. A good example of this latter situation is the Great Eruption of η Car, which lasted for two decades during the nineteenth century and showed temporal variability on time-scales of months and years.

The left panel of Figure 6 shows the flux from a light echo of η Car’s Great Eruption at the same location for various epochs: the observed flux time series is the light curve of the Great Eruption, convolved with the scattering dust thickness and image point spread function. The colored vertical lines indicate the epochs at which we obtained spectra of this light echo at that position, shown in the same colors in the right panel. This single light echo allowed us to analyze the evolution of the Ca II lines during η Car’s Great Eruption, and we found distinct differences from the typical spectral evolution of LBVs. The earliest spectra taken at epochs close to the peak in the light curve correlate best with spectra of G2-to-G5 supergiants, a later spectral type than predicted by standard opaque wind models (Rest et al. 2012a). The early Ca II IR triplet features are in absorption only, with an average blueshift of -200 km s^{-1} , and the lines are asymmetric extending up to -800 km s^{-1} (Rest et al. 2012a). Later spectra, corresponding to the decline phase of the burst, show that the Ca II IR triplet evolved from pure absorption, through a P-Cygni profile, to a nearly pure emission line spectrum. That transformation was accompanied by the development of strong CN molecular bands (see Figure 7). In contrast, standard LBV outburst spectra return to the earlier stellar types toward the end of an eruption. A paper detailing these observations is in preparation.

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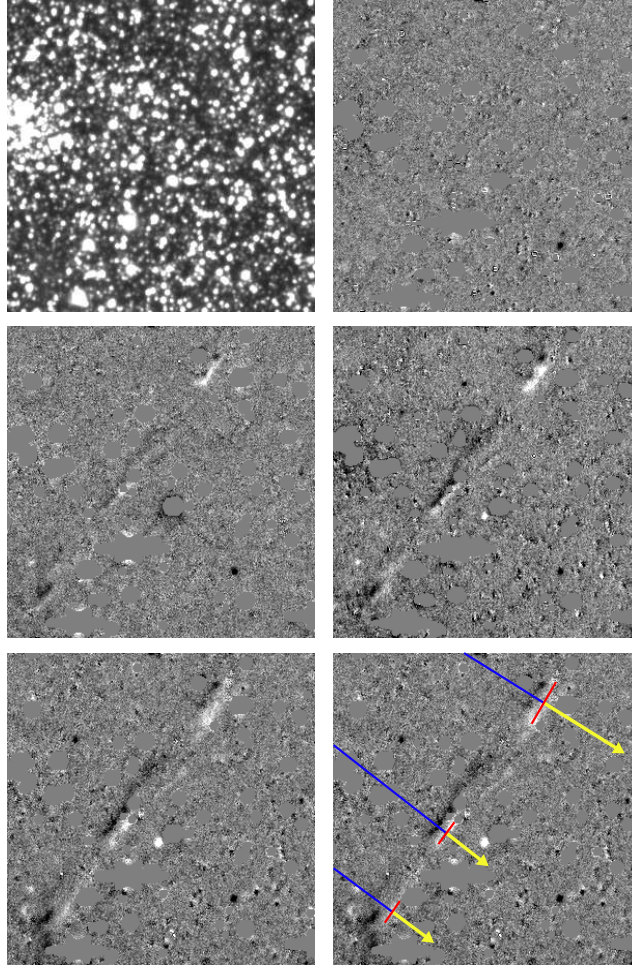


Figure 1. Light echoes in the LMC from ancient SNe. Panel 1 (upper left) shows the unsubtracted (template) Blanco CTIO 4m image which includes the cluster Hodge 243. Panel 2 (upper right) shows how cleanly the field subtracts with data taken 50 days apart. The next three panels show the echo motion 1, 2, and 3 years after the template date. White represents positive flux in the present epoch image and black in the template image. The vector motions are plotted in Panel 6 (lower right). Each echo is fit with a straight line (red). The apparent proper motion is given by the yellow vector and extrapolated backwards (blue). Saturated stars are masked out with grey circles. A number of faint variable stars appear as black or white spots. This figure and caption is courtesy of Rest et al. (2005b).

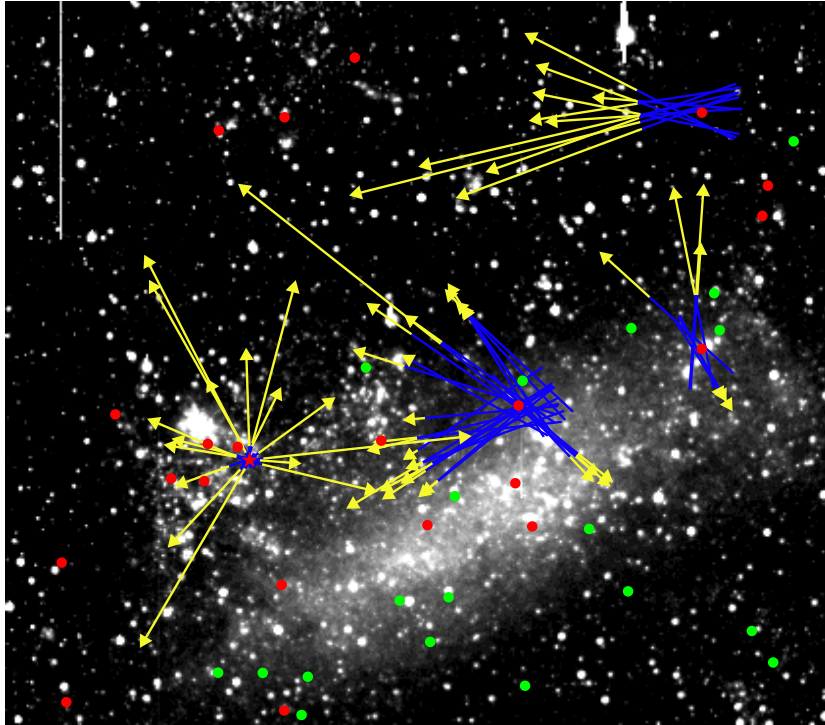


Figure 2. A plot of the light echo vectors in the LMC. The vectors have the same meaning as in Figure 1. The centres of the echo complexes are indicated by yellow circles. The source on the left marked with a star is SN1987A. The green circles are the location of historical novae, and the red circles are the supernova remnant locations. Evidently, the three light echo complexes point to SNR 0519-69.0, SNR 0509-67.5, and SNR 0509-68.7. This figure and caption is courtesy of Rest et al. (2005b).

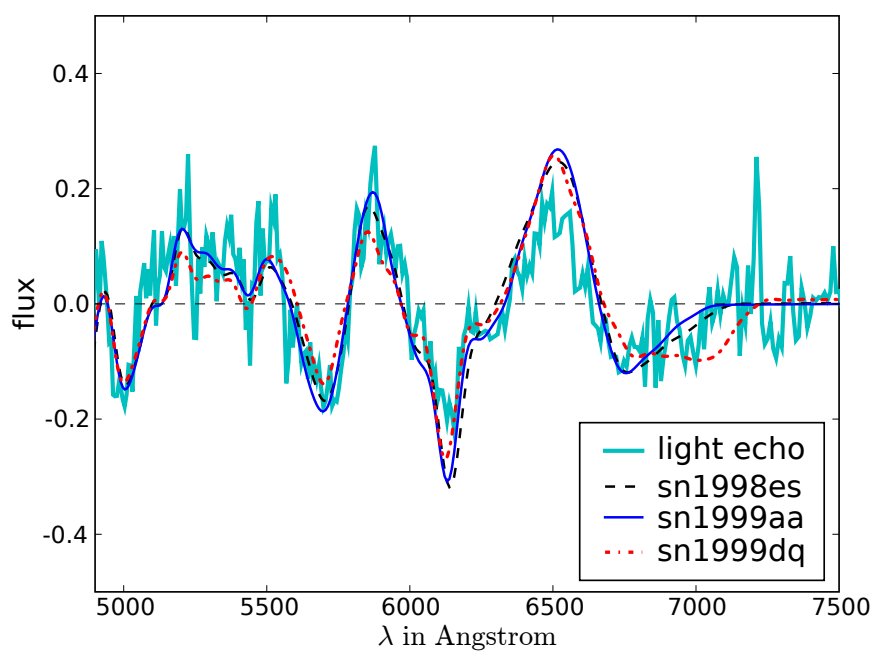


Figure 3. The three time-integrated, dust-scattered, reddened, and continuum-subtracted SN Ia that best fit the light echo spectrum associated with SNR 0519-69.0. Note that all three template spectra are 91T-like SNe Ia with $\Delta m_{15} < 0.9$. This figure and caption is courtesy of Rest et al. (2008a).

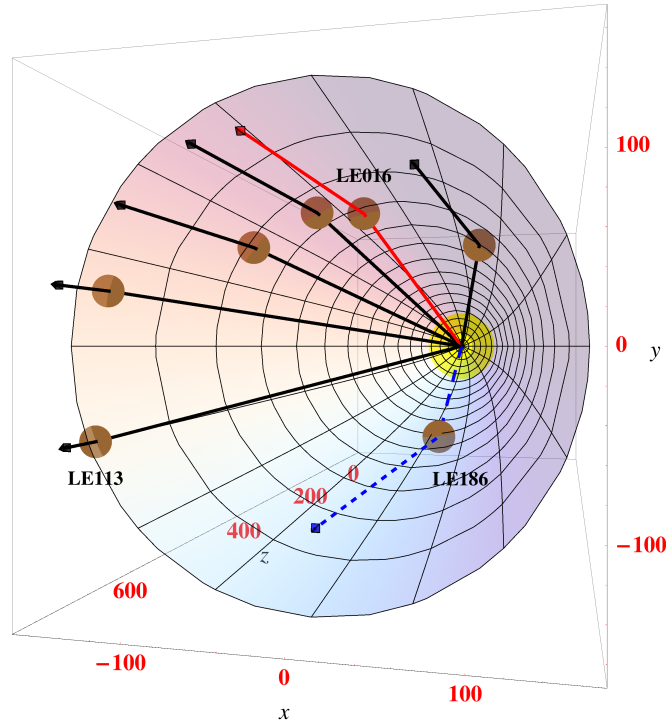


Figure 4. 3D locations of the scattering dust for the seven light echoes of SN 1987A that were spectroscopically followed up. Highlighted in solid red and dashed blue are the extreme viewing angles corresponding to LE016 and LE186. North is towards the positive y axis, east is towards the negative x axis, and z is the distance in front of the SN. All units are in light years. This figure and caption is courtesy of Sinnott et al. (2013).

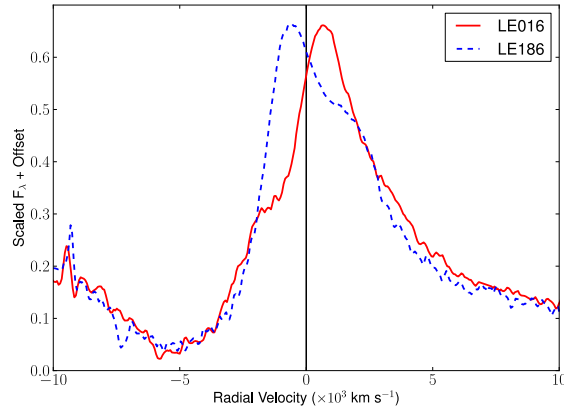


Figure 5. Observed $H\alpha$ lines from LE016 and LE186. Emission peaks have been interpolated with high-order polynomials. Spectra are scaled and offset for comparison purposes, as well as smoothed with a boxcar of 3 pixels. Although this plot does not take into account the important differences in light echo time-integrations between the spectra, it highlights the overall difference in fine-structure in the two light echo spectra from opposite PAs. Observing $H\alpha$ profiles with opposite asymmetry structure at opposite PAs is surprising considering the opening angle between the two light echoes is $< 40^\circ$. This figure and caption is courtesy of Sinnott et al. (2013).

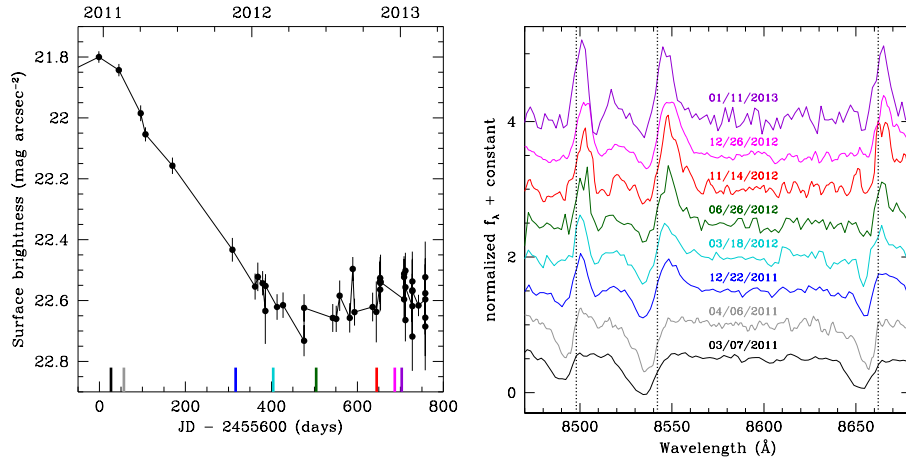


Figure 6. *Left:* Light curve of a portion of η Car’s Great Eruption, derived from its light echoes. Shown is the surface brightness in i band from the same sky position at different epochs (Blanco 4m (MOSAIC II, DECam), Swope (Direct CCD), FTS (Spectral), SOAR (SOI)). The light echo is the projected light curve of the source transient. Since the light echo has an apparent motion, the light curve of the source event “moves” through a given position on the sky. The epochs spectra were taken are indicated with the colored lines. *Right:* LE spectra of η Car’s Great Eruption showing the Ca II IR triplet from different epochs at the same sky location (Magellan Baade (IMACS), Gemini-S (GMOS)). The epochs of the spectra are indicated with in the left panel with vertical bars of the same color as the spectra.

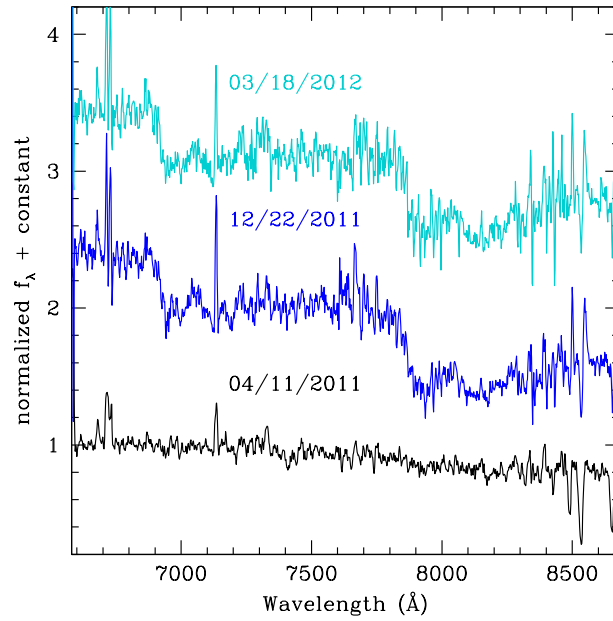


Figure 7. LE spectra of η Car's Great Eruption showing how the CN molecular bands develop for later epochs.